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Two-photon decays of the lightest Higgs boson of supersymmetry at the LHC

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ABSTRACT: We discuss the production and two-photon decay of the lightest Higgs boson (h^0) of the minimal supersymmetric standard model at the CERN Large Hadron Collider. Since the observability of the signal is quite model dependent, we conduct a thorough scan of the parameter space of minimal supersymmetry, including experimental and theoretical constraints. If kinematically allowed, supersymmetric decay modes of h^0 may be important, and can even dominate all others. The coupling of h^0 to $b\bar{b}$ can be different from that of a standard model Higgs boson; this can diminish (or enhance, but only if $\tan\beta$ is very large) the $h^0 \to \gamma\gamma$ signal. We emphasize the importance of a full treatment of radiative corrections in the Higgs sector for obtaining the $h^0 b\bar{b}$ coupling. If supersymmetric particles are not too heavy, their contributions in loops can either enhance or suppress both the production cross-section and the $h^0 \to \gamma\gamma$ branching fraction. We discuss the relative importance of these factors in the context of various scenarios for the discovery of supersymmetry. Even if h^0 is not detected at the LHC, h^0 may still exist in its expected mass region.

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One of the main reasons for the construction of new high-energy colliders is to find the Higgs scalar boson(s) associated with electroweak symmetry breaking in the standard model and its perturbative extensions. In a completely general framework of electroweak symmetry breaking, the Higgs sector is only weakly constrained. However, softly-broken supersymmetry is the only known theory in which a fundamental Higgs scalar does not receive disastrously large radiative corrections from physics at arbitrarily high energy scales. This theoretical perspective encourages and perhaps demands the presumption that nature is supersymmetric if a fundamental Higgs boson exists at all.

Low-energy supersymmetry does imply non-trivial constraints on the Higgs sector. The minimal supersymmetric standard model (MSSM) [1] contains two Higgs doublet chiral superfields, which after electroweak symmetry breaking result in two CP-even neutral scalars (conventionally denoted h^0 and H^0), one CP-odd neutral scalar (A^0) and a pair of charged scalars ($H^\pm$). The masses of the heavier CP-even neutral scalar H^0 and of $A^0, H^\pm$ are constrained only weakly by subjective criteria such as fine-tuning [2]; they therefore might escape detection at all colliders currently being planned. Fortunately, the mass of the lighter CP-even Higgs boson h^0 is guaranteed to be less than about 140 GeV in the MSSM, and less than about 150 GeV in other supersymmetric models which remain perturbative up to very high energies [3]. This means that h^0 is certainly kinematically accessible to future colliders and should eventually be discovered at a high energy e^+e^- collider (NLC) with $\sqrt{s} \geq 250$ GeV if it exists. Of course one would like to detect the Higgs sector before an NLC is built, but if the mass of h^0 exceeds the mass of the Z boson by more than a few GeV, it will probably escape detection at LEP-II. If the Tevatron collects ≥ 30 fb^{-1} of data it has been argued [4] that a Higgs boson is also detectable there up to and perhaps above 130 GeV, if it decays with similar branching fractions as the standard model Higgs.

In this paper we will examine the possibility of detecting h^0 produced in pp collisions at the CERN Large Hadron Collider (LHC) operating at $\sqrt{s} = 14$ TeV. The most important production mechanism for h^0 is by gluon fusion through quark- and squark-loop graphs. The tree-level decays of $h^0 \to b\bar{b}$ will dominate (unless decays of h^0 into pairs of supersymmetric particles are kinematically allowed, as we shall see), but are probably not useful because of large hadronic backgrounds. Instead, the detection of h^0 relies on the rare decay $h^0 \to \gamma\gamma$, which proceeds via one-loop graphs with all possible charged particles

running in the loop. This strategy requires excellent energy resolution (on the order of 1%) for the $\gamma\gamma$ pairs as well as good jet rejection to overcome the standard model backgrounds, which come from $q\overline{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$ [5] as well as jets imitating a γ in the detector.

Many groups have studied [6-17] the viability of this signal (as well as $H^0 \to \gamma\gamma$ and $A^0 \to \gamma\gamma$) at proton-proton supercolliders. However, most of these studies have employed special choices for the MSSM model parameters, or neglected the possibility of supersymmetric decays for h^0, so that it is difficult to gain an understanding of how general the results are. The total cross-section times branching ratio for $pp \to h^0 \to \gamma\gamma$ can depend quite strongly on the masses and couplings of the superpartners and Higgs bosons, particularly if they are not too heavy. Therefore, it is of utmost importance to consider all possibilities for the unknown model parameters. In this paper we will consider the relevant production cross section, decay widths and branching ratios for an ensemble of models within the general framework of the MSSM, each chosen to satisfy all present experimental constraints.

A completely general supersymmetrization of the standard model would introduce more than a hundred new parameters associated with the soft supersymmetry-breaking masses and couplings of the superpartners. Fortunately, we already have experimental evidence that these parameters are far from arbitrary; otherwise, large flavor-changing neutral currents would be expected to manifest themselves in processes such as $K \leftrightarrow \overline{K}$ mixing, $b \to s\gamma$, and $\mu \to e\gamma$. Thus there is strong circumstantial evidence in favor of some "organizing principle" governing the MSSM model parameters. On the theoretical side, supergravity models [18] provide just such an organizing principle, so that the features of the model may depend on only a few parameters at the scale $M_X \approx 2 \times 10^{16}$ GeV where low-energy data indicates a unification of gauge couplings. This "super-unified" model framework may have to be modified to account for high-energy threshold effects and other perturbations, but it is both sufficiently flexible and compelling to support the expectation that it will share its most important features with the correct theory.

To be concrete, for most of our analysis we generate models randomly within the super-unified MSSM framework, incorporating radiative electroweak breaking and gauge coupling unification and universal soft supersymmetry-breaking terms at M_X, using a computer program similar to the one described in [19]. We take our input parameters to

lie in the ranges

$$\begin{array}{ll} 160\,\mathrm{GeV} < m_{\rm top} < 190\,\mathrm{GeV} & 0\,\mathrm{GeV} < m_0 < 1000\,\mathrm{GeV} \\ 1 < \tan\beta < 60 & 40\,\mathrm{GeV} < m_{1/2} < 500\,\mathrm{GeV}\,. \end{array} \tag{1}$$

The allowed range of the scalar trilinear coupling parameter A_0 at M_X is determined by the constraint that there be no charge- and color-breaking global minima of the scalar potential at the electroweak scale. We search for such minima in the $SU(3)_C$ D-flat directions proportional to $(H_u, \tilde{t}_L, \tilde{t}_R, \tilde{\nu}_\tau) \sim (1, a, a, b)$ and $(H_d, \tilde{b}_L, \tilde{b}_R, \tilde{\tau}_L, \tilde{\tau}_R) \sim (1, c, c, d, d)$, with a, b, c, d arbitrary, using methods indicated in [20]. The resulting constraints subsume the more traditional but less powerful ones which correspond to $a = 1, b = 0$; $c = 1, d = 0$; and $c = 0, d = 1$.

On this parameter space we impose experimental constraints, including direct and indirect sparticle and Higgs boson mass limits [21]; the invisible width of the Z constraint; a lightest supersymmetric particle (LSP) which is the lightest neutralino; a predicted branching ratio for $b \to s\gamma$ which is not in gross conflict with recent experimental data [22]; and the constraint that the relic density of dark matter in the form of LSPs is not large enough to overclose the universe [23]. (We assume that R-parity is exactly conserved so that the LSP is absolutely stable.) The resulting constrained parameter space has many correlations between the masses and couplings of the superpartners and Higgs bosons, not all of which are immediately obvious in any analytic form.

We compute the Higgs masses and couplings incorporating one-loop radiative corrections using the effective potential method [24]. This is an important aspect of the analysis since large squark mixing and/or nondegeneracy can induce large corrections to m_{h^0} and to the Higgs mixing angle α, and so must not be ignored. Since it will be of particular importance in the discussion to follow, we pause to make some remarks on this point. The $(\mathrm{mass})^2$ matrix for the CP-even neutral scalars h^0, H^0 is given by

$$\mathcal{M}^2 = \begin{pmatrix} \sin^2\beta M_{A^0}^2 + \cos^2\beta M_Z^2 & -\sin\beta\cos\beta(M_{A^0}^2 + M_Z^2) \\ -\sin\beta\cos\beta(M_{A^0}^2 + M_Z^2) & \cos^2\beta M_{A^0}^2 + \sin^2\beta M_Z^2 \end{pmatrix} + \begin{pmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{12} & \Delta_{22} \end{pmatrix} \tag{2}$$

where the Δ_{ij} represent radiative corrections which may be found explicitly e.g. in [24]. Then $m_{h^0}^2$ and $m_{H^0}^2$ are the eigenvalues of (2), and the Higgs mixing angle α is determined by the orthogonal matrix

$$\begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}$$

which diagonalizes (2). In the super-unified MSSM parameter space, one must have $\pi/4 < \beta < \pi/2$ in order to maintain the perturbativity of the Yukawa couplings up to M_X. There is always a strong correlation between α and β if $\tan\beta$ is not too large, and if $m^2_{A^0}$ dominates over M^2_Z and the radiative corrections Δ_{ij}. In this limit one will always have $-\pi/4 < \alpha < 0$, and in particular $\alpha \approx \beta - \pi/2$. The couplings of h^0 to electroweak vector bosons V and to fermions are then quite close to the same couplings for a standard model Higgs boson ϕ^0. The ratio of the h^0VV couplings to the ϕ^0VV ones are given by $\sin(\beta-\alpha)$. Within our constrained parameter space, $\sin(\beta - \alpha)$ is always very close to 1 except when $\tan\beta > 30$ and A^0 is light. Nevertheless, the ratio of the $h^0b\bar{b}$ coupling to that of $\phi^0b\bar{b}$, given by $-\sin\alpha/\cos\beta$, can be significantly greater than 1 for any value of $\tan\beta$. However, we find that $-\sin\alpha/\cos\beta$ cannot be significantly less than 1 in models with $\tan\beta < 30$. For $\tan\beta > 30$, $-\sin\alpha/\cos\beta$ is a more volatile function of the radiative corrections, because the contributions to the off-diagonal elements of $\mathcal{M}^2$ which are proportional to $m^2_{A^0}$ are highly suppressed, and no longer dominate over even moderately-sized Δ_{12}. Thus one can and does find perfectly viable models with $\tan\beta > 30$ and $-\sin\alpha/\cos\beta \ll 1$, and even with $\alpha > 0$. Note that these possibilities will necessarily be missed in commonly-used treatments which neglect squark mixing and approximate all squark masses with a single supersymmetry scale (thus expressing all radiative corrections to the Higgs sector in terms of a single parameter ϵ), because these approximations are tantamount to setting Δ_{12} to 0 by hand.

Now, the large $\tan\beta$ case might be regarded as merely an academic curiosity, because as is well known it seems to require some fine-tuning of the soft parameters in order to achieve correct electroweak symmetry breaking. While we are sympathetic to this outlook, it is also true that certain theoretical frameworks (e.g. those with Yukawa coupling unification such as $SO(10)$ models) favor a very large $\tan\beta$. So, for both theoretical and phenomenolgical reasons, we find it appropriate to divide those parts of the analysis below which directly involve the $h^0b\bar{b}$ coupling into regions of high and low $\tan\beta$, with $\tan\beta = 30$ an empirically good dividing line.

A significant portion of the constrained MSSM parameter space is consistent with successful searches for superpartners at LEP-II and at an upgraded Tevatron. Since the results of these searches will be known by the time the LHC begins its search for h^0, we find it useful to divide some of our results below into two additional categories, according

to whether or not at least one superpartner will be detected by the time the LHC begins its search for h^0. Now, the ability of the Tevatron to detect superpartners depends quite strongly on exactly which upgrade(s) are implemented and on details of detector performance, whereas the reach of LEP-II is essentially determined by kinematics. Therefore, for simplicity we choose to use only LEP-II detection criteria, which we approximate by saying that supersymmetry will be detected if a charged superpartner is lighter than 90 GeV. (Of course sneutrinos or non-LSP neutralinos may also be detected at LEP-II, but we find that within our parameter space this correlates extremely well with a charged sparticle also being accessible.)

Let us first consider the total production cross-section for h^0 from gluon fusion. In the narrow-width approximation this is related to the width of h^0 into gluons by

$$\sigma(pp \to h^0) = \frac{\pi^2}{8m_{h^0}^3}\Gamma(h^0 \to gg)\,\tau \int_\tau^1 \frac{dx}{x} g(x, m_{h^0}^2) g(\tau/x, m_{h^0}^2)\,, \tag{3}$$

where $\tau = m_{h^0}^2/s$ with $\sqrt{s} = 14$ TeV. We work consistently with α_s and gluon distribution functions $g(x, m_{h^0}^2)$ in leading order taken from [25]. In determining $\Gamma(h^0 \to gg)$, we include all one-loop quark and squark loop graphs, with both stop and sbottom mixing effects; the relevant formulas may be found for example in [26]. The top-quark loop is dominant for the standard model but we find that in the constrained MSSM parameter space the effects of stops and sbottoms can be quite significant, and can even result in nearly complete destructive interference if a stop is lighter than about 100 GeV.

In Figure 1 we show the total production cross-section for each model within our ensemble as a function of m_{h^0}. Models which have a lightest squark (always a stop or sbottom) with mass less than 200 GeV are denoted by an $\times$, and other models are denoted by dots. For comparison, the production cross-section for a standard model Higgs boson of the same mass and with $m_{\mathrm{top}} = 175$ GeV (the standard model cross-section varies only weakly with m_{top}) is shown as a solid line. We should remark that for consistency we do not include higher order QCD corrections, because these have only been computed for quark loops and not for squark loops (see [15] and references therein). Since these radiative corrections in the standard model have been shown to be positive and large ($\sim$60%), our results should be regarded as conservative. Full QCD corrections would of course have to be included in any attempt to separate the experimentally measured cross-section from the branching fraction in an experimentally measured signal. In general, we

find that the sum of loops involving the squarks of the first two families always makes a negligible contribution in the constrained parameter space. The third family squark-loop contributions clearly can either enhance or diminish the total cross-section. Also, one should note that the squark-loop effects are generally smaller if $m_{h^0} > 125$ GeV; this is because larger m_{h^0} requires large radiative corrections in the Higgs sector which in turn corresponds to heavier stops and sbottoms.

In Figure 2 we show the total width (in keV) of $h^0 \to \gamma\gamma$ as a function of m_{h^0}. The dominant contribution in the standard model comes from W-boson loops; this is also true for supersymmetric models when $\sin(\beta - \alpha)$ (the ratio of the coupling of h^0 to electroweak vector bosons to the corresponding coupling for a standard model Higgs boson) is close to unity. This is always the case within the constrained super-unified MSSM parameter space, except for some models with $\tan\beta$ larger than 30 and light A^0. The contributions to the amplitude coming from chargino loops are important for chargino masses less than about 100 GeV, and the sum of the third-family squark and slepton loop amplitudes can also be significant. Even the sum of first and second-family sfermion loops can change the total width by more than 10%, if a slepton is within the discovery reach of LEP-II. However, we find that complete destructive interference between the W-loop and supersymmetric loops is never possible within the constrained parameter space. In Figure 2 we have used an $\times$ to denote models in which the lightest charged supersymmetric particle is less than 90 GeV (and so may be detected at LEP-II), showing the susceptibility of the $h^0 \to \gamma\gamma$ width to light superpartners. Note that if supersymmetry is discovered at LEP-II, h^0 cannot be heavier than about 125 GeV with our allowed ranges of parameters in eq. (1). (This upper bound would increase if $m_0 > 1$ TeV.)

To determine the total branching ratio of $h^0 \to \gamma\gamma$, we must also account for all other decay modes. We compute the width of h^0 from tree-level decays into standard model fermion-antifermion pairs using the formulas in e.g. [26], also including the significant radiative corrections for the dominant $h^0 \to b\bar{b}$ decay mode as given in [27]. We also include the decay widths of h^0 into gluon pairs, and into off-shell WW^* and ZZ^* states, which become increasingly important for larger m_{h^0} [28]. Finally, we include decays of h^0 into all kinematically allowed neutralino, chargino, and sfermion-antisfermion pairs using the formulas in [26]. The possibility of these decay modes of h^0 has been neglected in

many analyses,[†] but it is important to take them into account because they can suppress the $h^0 \to \gamma\gamma$ branching fraction to an unuseable level. In Figure 3 we show a scatterplot of the total width of h^0 into charginos and neutralinos as a function of μ for models in which these decays are kinematically allowed. We find that within the constrained parameter space the total ino-ino decay widths of h^0 can be as large as 50 MeV when μ is positive (using the sign convention of [1,26]) and as large as 10 MeV when μ is negative. On the other hand, even if supersymmetry is not discovered at LEP-II (models denoted by $\times$'s), the decay width of h^0 into LSP pairs can still be as large as 400 keV if $\mu > 0$ and 20 keV if $\mu < 0$.

When h^0 decays into sneutrinos, charged sleptons, or stops are kinematically allowed, we find that the corresponding widths are usually even larger, typically tens or hundreds of MeV. A subtlety arises if the Higgs mass is at or slightly below threshold of a two body decay $h^0 \to AB$, since the simple 2-body decay formulas [26] will incorrectly yield a zero result for the calculated width. The correct answer near or below threshold is obtained only after calculating the full decay amplitude with off-shell A^* and B^*. When A and B are superpartners which eventually must each decay into a neutralino LSP ($\tilde{N}_1$), the result may be conveniently parameterized by

$$\Gamma(h^0 \to A^* B^* \to X_A \tilde{N}_1 X_B \tilde{N}_1) = \int_{m_{\tilde{N}_1}}^{m_{h^0} - m_{\tilde{N}_1}} \frac{2 q_A^2 dq_A}{\pi} \int_{m_{\tilde{N}_1}}^{m_{h^0} - q_A} \frac{2 q_B^2 dq_B}{\pi} \times \tag{4}$$
$$\Gamma(h^0 \to A^* B^*) \frac{\Gamma(A^* \to X_A \tilde{N}_1)}{[(q_A^2 - m_A^2)^2 + \Gamma_A^2 m_A^2]} \frac{\Gamma(B^* \to X_B \tilde{N}_1)}{[(q_B^2 - m_B^2)^2 + \Gamma_B^2 m_B^2]} \,.$$

Here $\Gamma(h^0 \to A^* B^*)$ is the two-body decay width of h^0 into off-shell A^* and B^* of masses q_A and q_B. The decay widths of off-shell stops, charginos and neutralinos are always very small if their masses are comparable to $m_{h^0}/2$, so that off-shell decays of h^0 into stops, charginos and neutralinos should not be a concern. However, we do find models with sneutrinos near the $h^0 \to \tilde{\nu}\overline{\tilde{\nu}}$ threshold, and with $\Gamma(\tilde{\nu}^* \to \nu \tilde{N}_1)$ often exceeding 50 MeV. In such cases we find that exactly at threshold ($m_{h^0} = 2 m_{\tilde{\nu}}$) the contribution to the width of h^0 is a few MeV, greatly reducing the $\gamma\gamma$ signal. The contribution to the h^0 width drops quickly below threshold, but it will still be in the hundred keV range if m_{h^0} is 3 GeV or in some cases even 4 GeV below the threshold. The h^0 width in these cases is of

† See, however, refs. [29,11,30] which discuss the importance of supersymmetric decays for h^0 (and H^0 and A^0) in different contexts.

course quite sensitive to how near $2m_{\tilde{\nu}}$ is to m_{h^0}, and to the sneutrino widths. Similar statements apply if h^0 decays to a stau or right-handed selectron or smuon are within a few GeV of threshold. These possibilities could be a concern if evidence for sleptons is found at LEP-II.

Since standard model decays of the h^0 typically have a combined width of order 3 MeV, the h^0 decays into supersymmetric states can completely dominate the branching fractions. While h^0 might decay into potentially visible supersymmetric states, or into invisible states [30], we find that the supersymmetric branching fraction of h^0 can exceed 15% only if LEP-II detects supersymmetry. More studies are needed to determine if visible supersymmetric decay modes can be used to detect h^0 (with the main background presumably coming from continuum production of sparticles); that will surely be difficult at the LHC, although for the heavier states H^0 and A^0 it has been shown [11] to be a possibility for decays to pairs of second-lightest neutralinos.

Another factor which can severely diminish the $h^0 \to \gamma\gamma$ branching fraction is an enhanced coupling of h^0 to $b\bar{b}$. In the MSSM, this coupling is equal to the corresponding coupling of a standard model Higgs boson multiplied by the factor $-\sin\alpha/\cos\beta$. This factor can be significantly greater than 1 for all values of $\tan\beta$ if A^0 is not too heavy, which greatly enhances $\Gamma(h^0 \to b\bar{b})$ with a concomitant unfortunate effect on the $\gamma\gamma$ branching fraction. As we have already mentioned, a full treatment of radiative corrections in the Higgs sector reveals that $-\sin\alpha/\cos\beta$ can also be less than 1, reducing the $h^0 \to b\bar{b}$ branching ratio and thus increasing the two-photon signal. However, this can only happen if $\tan\beta > 30$.

All of these effects are included in Figure 4, which shows the branching ratio $\mathrm{Br}(h^0 \to \gamma\gamma)$ as a function of m_{h^0} for models within the constrained parameter space, for $\tan\beta < 30$ [Figure 4(a)] and $\tan\beta > 30$ [Figure 4(b)]. It is clear that supersymmetric decay modes are less likely to be a problem if m_{h^0} is near the higher end of its allowed range. This is because a heavier h^0 generally corresponds to large radiative corrections which in turn are associated with a heavier supersymmetry-breaking scale, and thus heavier sparticles. For the same reason, supersymmetric contributions to production and decay amplitudes also tend to be smaller for larger m_{h^0}. The main "risk factor" for the $h^0 \to \gamma\gamma$ signal if $m_{h^0} > 125$ GeV is therefore the possibility of an enhanced $h^0 b\bar{b}$ coupling. Note that if $\tan\beta > 30$, one can have $\mathrm{Br}(h^0 \to \gamma\gamma)$ as large as 1%. Also it is important to note that

$\tan\beta > 30$ implies that $m_{h^0} > 100$ GeV, so that h^0 cannot be discovered at LEP-II.

In Figure 5 we show the total cross-section times branching ratio for the process $pp \to h^0 \to \gamma\gamma$ as a function of m_{h^0} in the scenario that supersymmetry cannot be discovered at LEP-II. Even in this case there are models for which h^0 decays into LSPs are kinematically allowed, although they tend to be much less important than in the scenario in which supersymmetry has already been discovered before the LHC turns on, and they are never responsible for killing the signal. Again we have divided the models into small and large $\tan\beta$ categories. As we remarked earlier, we do not include QCD radiative corrections to the cross-section, which may increase it, since they have not been fully computed for the supersymmetric case. Since the SM QCD corrections increase the cross-section by a factor of $\sim$1.6, QCD corrections to the supersymmetric amplitudes could be similarly large. Until these corrections are fully understood, it will unfortunately not be possible to separate σ or $\mathrm{Br}(h^0 \to \gamma\gamma)$ from the measured $\sigma\times$ $\mathrm{Br}(h^0 \to \gamma\gamma)$. One would like to conclude from Fig. 5(a) that the leading order cross-section times the branching fraction for $pp \to h^0 \to \gamma\gamma$ will have to exceed about 20 fb (before efficiencies) if supersymmetry is not discovered at LEP-II and if $\tan\beta < 30$. This is indeed true within the constrained super-unified MSSM framework, but as we shall remark below, it need not hold in a more general model framework.

Figure 6 shows the total cross-section times branching ratio for models in the complementary scenario in which at least one supersymmetric particle should be detected at LEP-II. In this case, the $h^0 \to \gamma\gamma$ signal may be endangered not only by the possibility of competing supersymmetric decay modes (models denoted by $\times$'s) but by an enhanced width into $b\bar{b}$ or by sfermion loop effects which can decrease the total h^0 production rate and the $\gamma\gamma$ width.

Finally, in Figure 7 we show the dependence of the cross-section times branching ratio on m_{A^0}, for models with $m_{h^0} > 95$ GeV so that h^0 cannot be discovered at LEP-II. Note that even when A^0 is very heavy, there are models in which h^0 cannot be discovered at the LHC, primarily but not exclusively because of the possibility of supersymmetric decay modes.

Let us now turn to the question of how dependent our results are on the choice of boundary conditions for the soft terms. One particularly well-motivated generalization of the universal soft-breaking boundary condition is to add D-term contributions [31,32] to

the scalar squared masses, since these will naturally maintain the cancellation of flavor-changing neutral currents. Such contributions should arise whenever the unbroken gauge group at high energies has rank > 4, and could easily be comparable in magnitude to the usual soft-breaking parameters even if the scale at which the gauge group breaks down to $SU(3)_C \times SU(2)_L \times U(1)_Y$ is arbitrarily high. In order to check the generality of our results, we have generated an ensemble of models as discussed above, but also including D-term contributions to scalar masses that could arise from the spontaneous breaking of an arbitrary subgroup of E_6, as parameterized in [32]. We find that the most important change induced by these generalized boundary conditions in the results outlined above is that A^0 can be lighter, corresponding to a larger $h^0 b\bar{b}$ coupling. This difference is particularly significant if supersymmetry is not discovered at LEP-II and $\tan\beta < 30$; with universal scalar mass boundary conditions one then finds $m_{A^0} > 200$ GeV throughout the constrained parameter space, but with large D-term contributions to scalar masses one can find models with m_{A^0} as low as 110 GeV. The effect of this is to substantially reduce the $h^0 \to \gamma\gamma$ branching fraction by increasing the $h^0 \to b\bar{b}$ width. This may occur if $4D_X - D_S + 3D_{\hat{Y}} > 0$ in the notation of [32], corresponding to a change in the scalar mass boundary conditions with $\Delta(m^2_{H_u} - m^2_{H_d}) > 0$. As in the case of universal scalar mass boundary conditions, we find that the $h^0 \to \gamma\gamma$ signal cannot be enhanced by a smaller $h^0 b\bar{b}$ coupling unless $\tan\beta > 30$. While the leading order cross-section times the branching fraction before efficiencies is always larger than about 20 fb if supersymmetry is not discovered at LEP-II and $\tan\beta < 30$ in the case of universal scalar mass boundary conditions [see Fig. 5(a)], this need not hold if D-term contributions to scalar masses are large compared to the universal soft supersymmetry-breaking masses and have the appropriate signs.

In this paper we have examined the variation of the $pp \to h^0 \to \gamma\gamma$ signal at the LHC within the framework of the constrained MSSM. Certainly if LHC does not detect h^0 it will not be possible to conclude that h^0 does not exist. We note that prospects for discovering h^0 through the two-photon decay mode depend strongly on whether or not supersymmetry will have been discovered at LEP-II (or an upgraded Tevatron). If supersymmetry is not discovered at LEP-II, then $h^0 \to$ SUSY decays may still be allowed, but will be sufficiently kinematically disfavored that they cannot reduce the $h^0 \to \gamma\gamma$ signal by more than about 15%. In this scenario, the most important risk factor for discovering h^0 at the LHC is the

possibility that $-\sin\alpha/\cos\beta$ is significantly greater than 1. The $h^0 \to \gamma\gamma$ signal could also be dramatically enhanced by $-\sin\alpha/\cos\beta < 1$ so that $\mathrm{Br}(h^0 \to \gamma\gamma)$ can be as large as 1%, but we find that this requires $\tan\beta > 30$ within the constrained MSSM parameter space. If one or more supersymmetric particles are detected by the time the LHC begins its search for h^0, careful study will be required to determine if the $h^0 \to \gamma\gamma$ signal at the LHC is still viable.

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Figure Captions

Figure 1: The total production cross-section (in pb) for h^0 in pp collisions at $\sqrt{s} = 14$ TeV as a function of m_{h^0}. Each point represents a different set of model parameters which satisfy all experimental and theoretical constraints. Models for which the mass of the lightest squark (usually a stop) is less than 200 GeV are represented by an $\times$, while all other models are represented by a dot. As a convenient reference, we also show as a solid line the total production cross-section of a standard model Higgs boson with the same

mass and $m_{\rm top} = 175$ GeV. Higher order QCD corrections are not included since they have not been fully computed for the supersymmetric case (see comments in text).

Figure 2: The total width (in keV) for h^0 decays to two photons as a function of m_{h^0}. Models for which the lightest charged supersymmetric particle is less than 90 GeV (and thus detectable at LEP-II) are represented by an $\times$, while all other models are represented by a dot. We also show as a solid line the same decay width for a standard model Higgs boson of the same mass and $m_{\rm top} = 175$ GeV.

Figure 3: The total width (in MeV) for h^0 decays into neutralino and chargino pairs, as a function of μ (using the sign convention of [1,26]). Models for which a supersymmetric particle should be detected at LEP-II are denoted by a dot, and other models in which h^0 can decay to LSP pairs are denoted by an $\times$.

Figure 4: The branching fraction $\mathrm{Br}(h^0 \to \gamma\gamma)$ (in %) as a function of m_{h^0}, for models with $\tan\beta < 30$ (a) and $\tan\beta > 30$ (b). Models for which h^0 is kinematically allowed to decay into pairs of supersymmetric particles are represented by an $\times$, and models for which supersymmetry is likely to be discovered at LEP-II (but for which supersymmetric decays of h^0 are not kinematically allowed) are represented by an open circle, while all remaining models are denoted by a dot. The solid line is the same branching fraction for a standard model Higgs boson of the same mass and with $m_{\rm top} = 175$ GeV.

Figure 5: The cross-section times branching fraction (in fb) for $pp \to h^0 \to \gamma\gamma$ as a function of m_{h^0}, for models in which supersymmetry cannot be discovered at LEP-II, with $\tan\beta < 30$ (a) and $\tan\beta > 30$ (b). Models for which h^0 is kinematically allowed to decay into pairs of supersymmetric particles are represented by an $\times$. No efficiencies are included, and again we emphasize that QCD corrections to the production cross-section are not included. The solid line is the same cross-section times branching fraction for a standard model Higgs boson of the same mass and $m_{\rm top} = 175$ GeV.

Figure 6: The same as Figure 5, but for models in which supersymmetric particles can be detected at LEP-II.

Figure 7: The cross-section times branching fraction for $pp \to h^0 \to \gamma\gamma$ (in fb) as a function of m_{A^0}, for models with $m_{h^0} > 95$ GeV, so that h^0 cannot be discovered at LEP-II. Models in which h^0 has kinematically allowed supersymmetric decays are denoted by an $\times$, and the remaining models are divided into $\tan\beta > 30$ (open circles) and $\tan\beta < 30$ (dots).

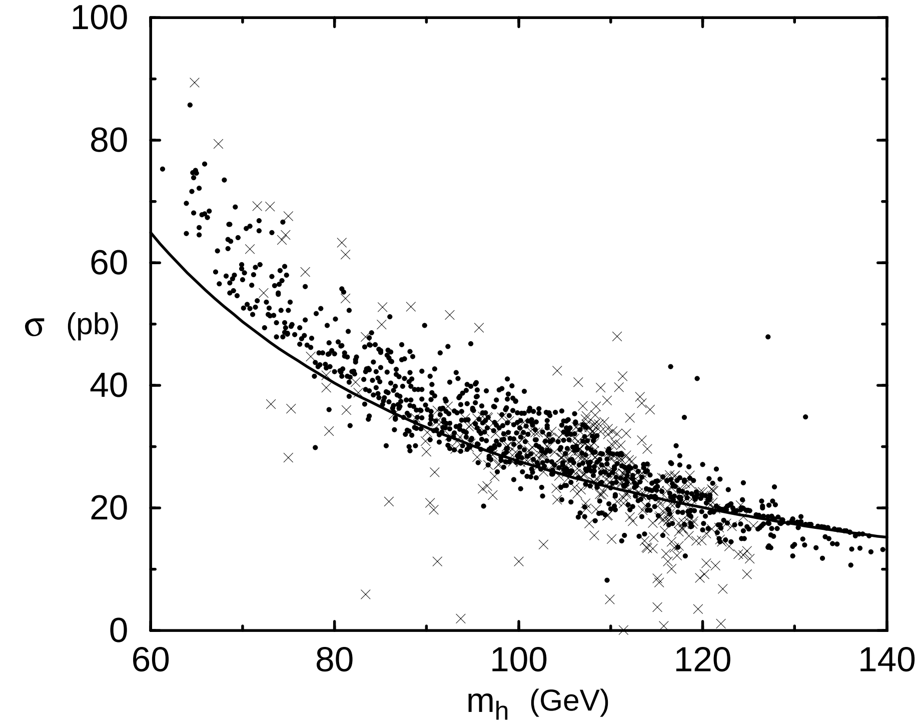
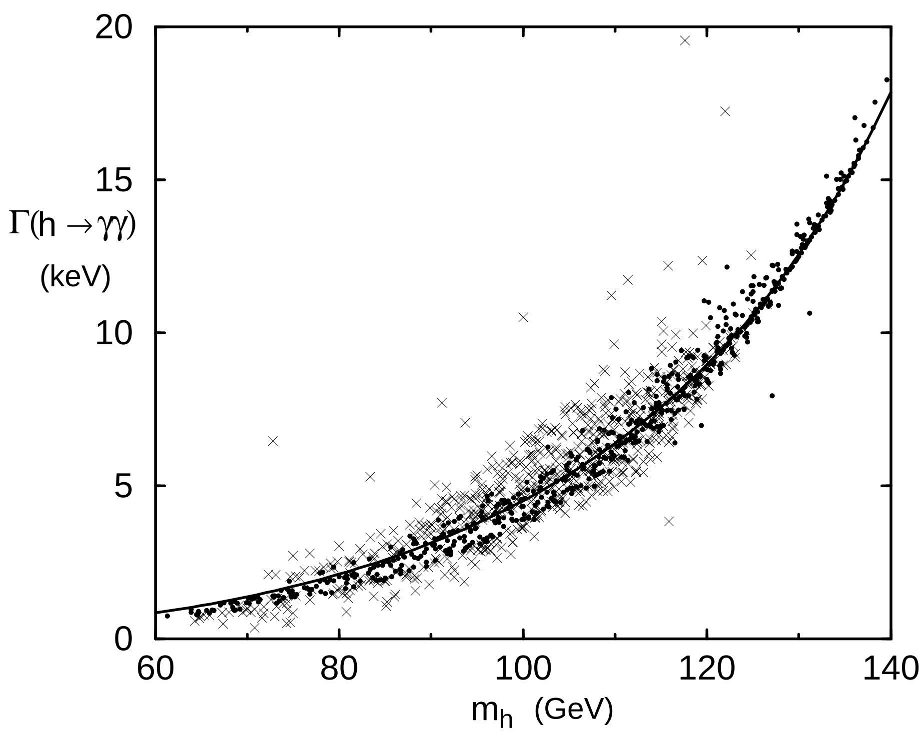


Figure 1:



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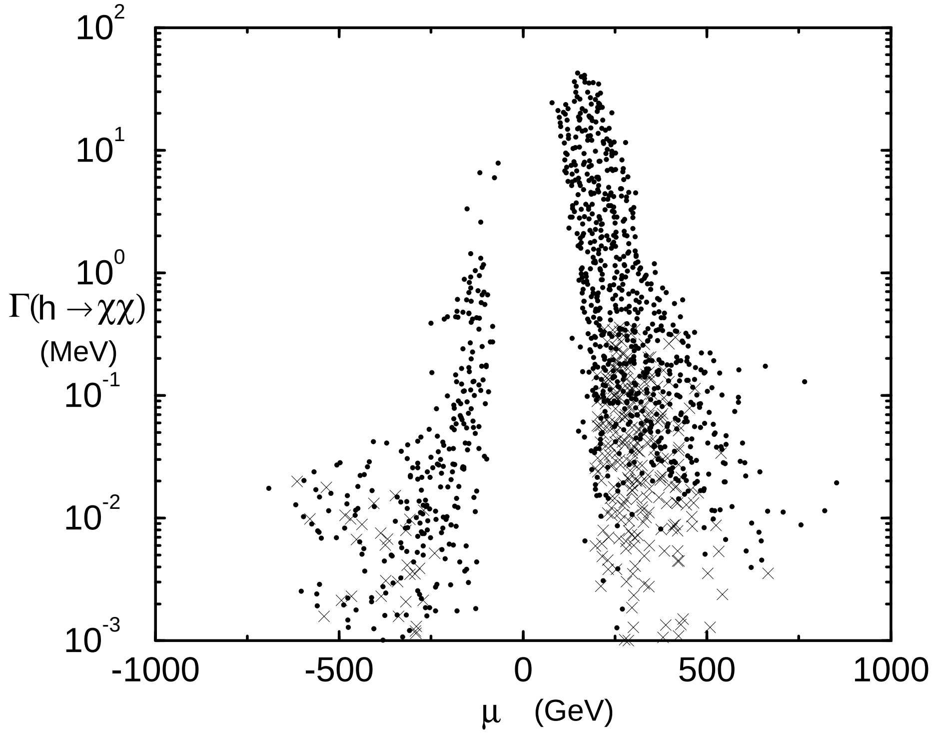


10^2
10^1
10^0
$\Gamma(h \to \chi\chi)$
(MeV)
10^{-1}
10^{-2}
10^{-3}
-1000
-500
0
500
1000
μ (GeV)

Figure 3:

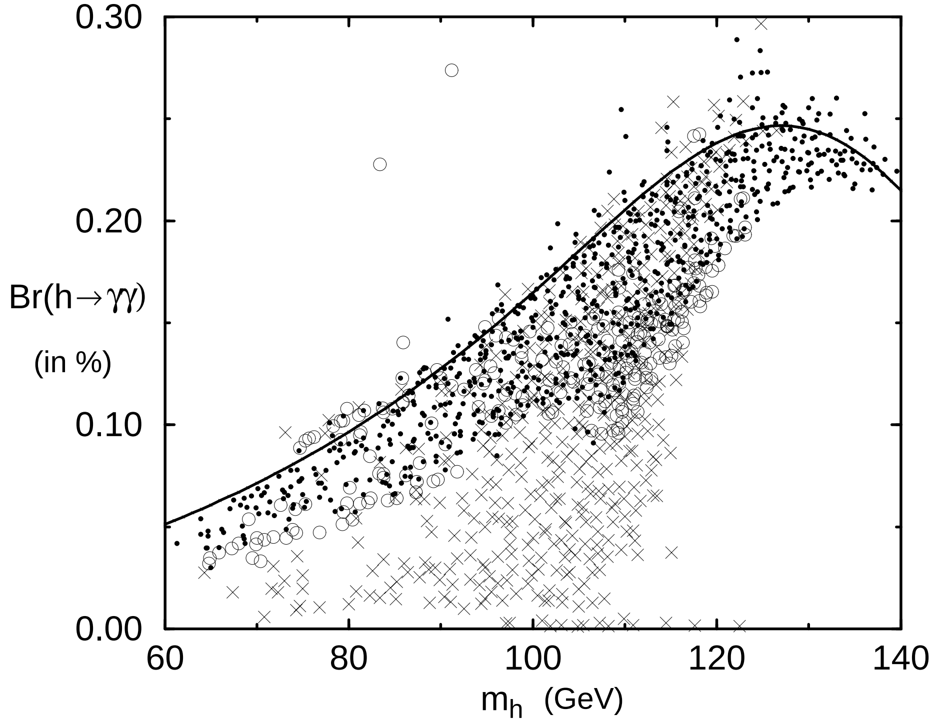


Figure 4: (a)

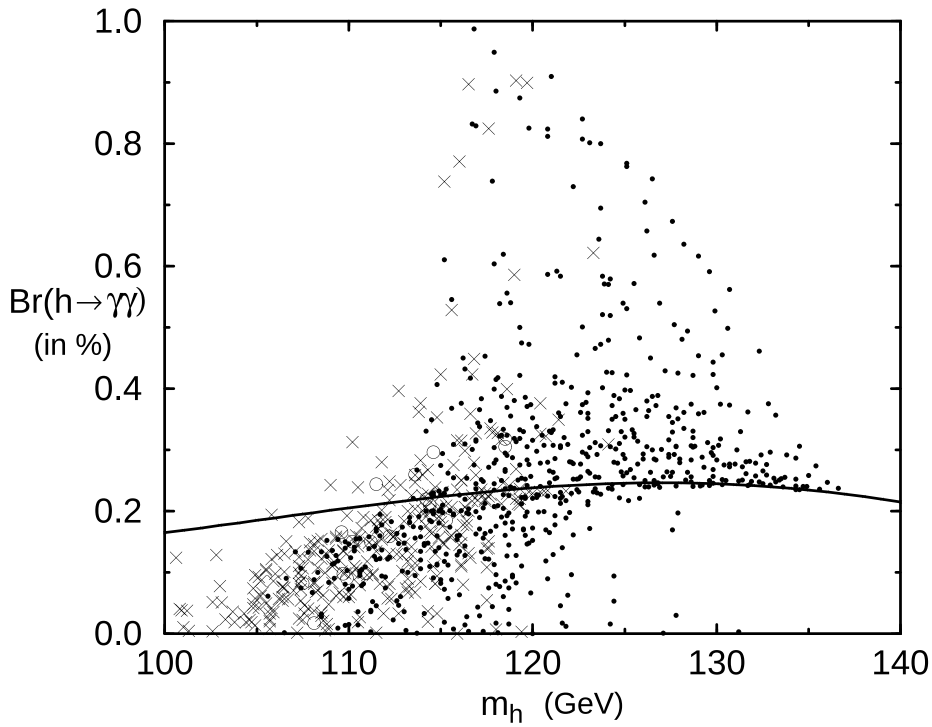


Figure 4: (b)

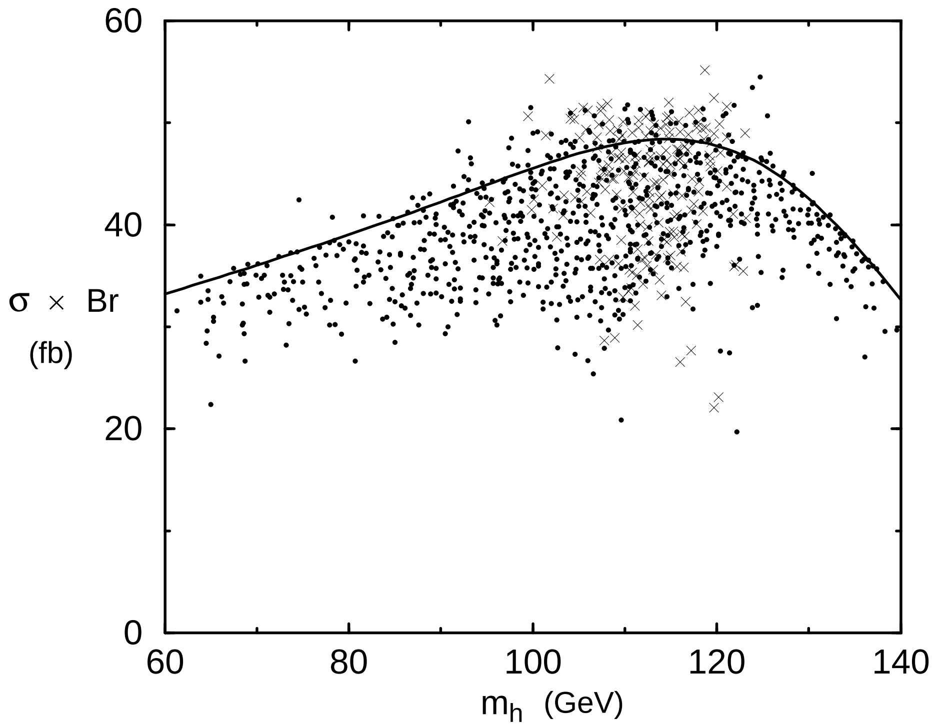


Figure 5: (a)

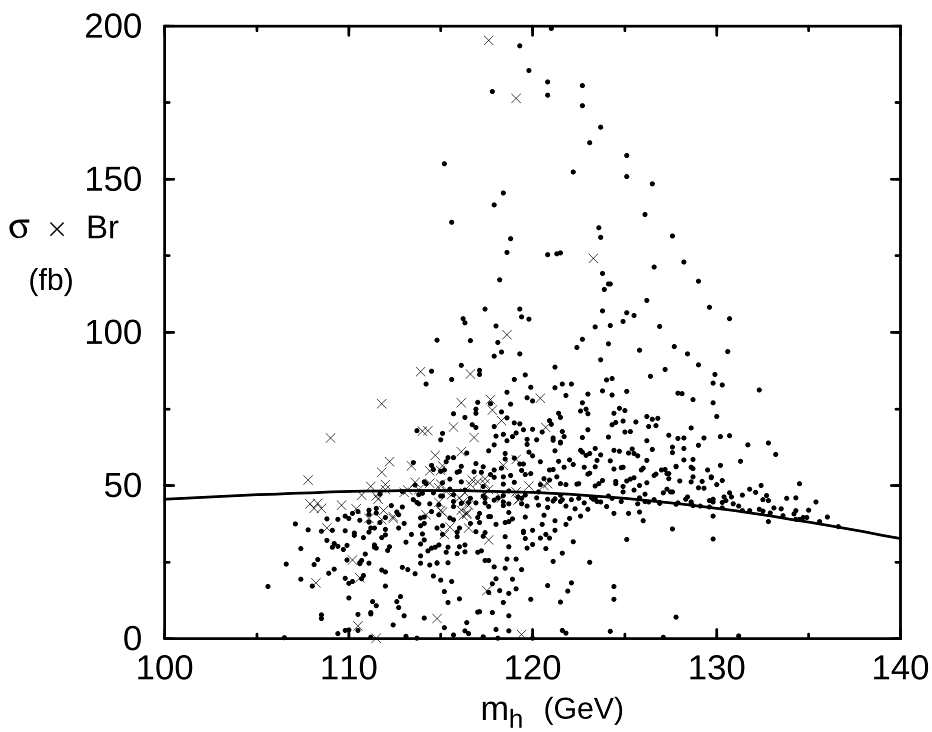


Figure 5: (b)

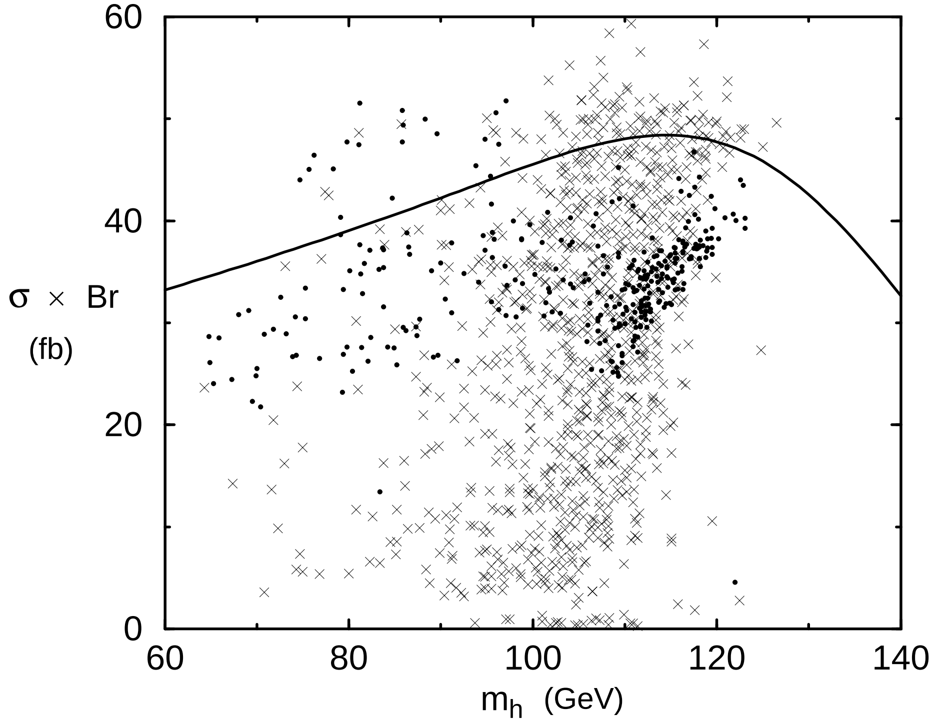
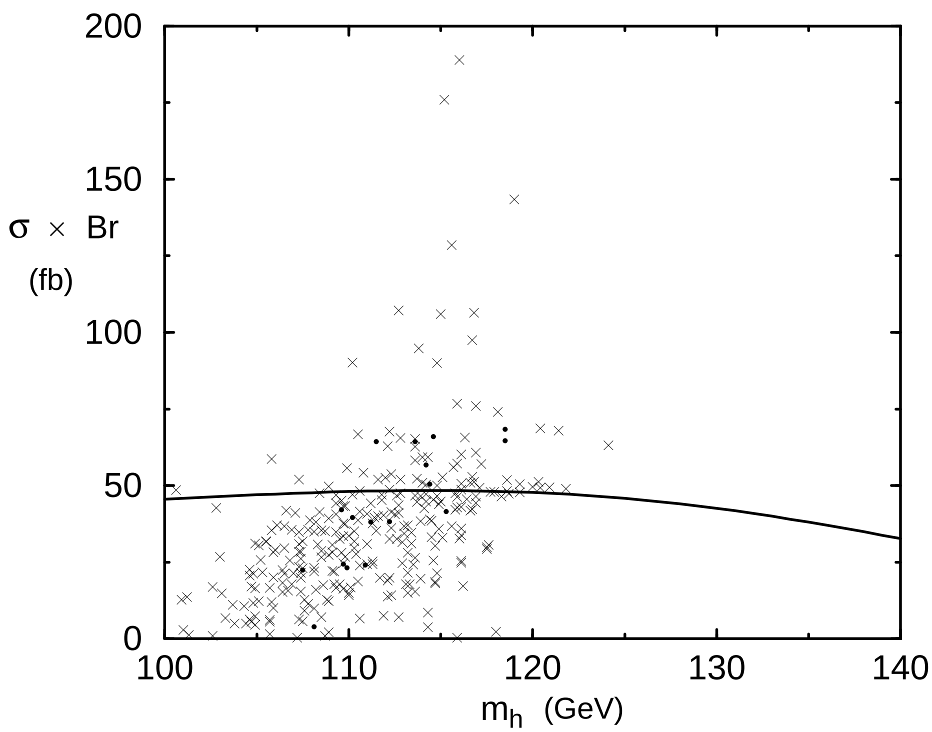


Figure 6: (a)



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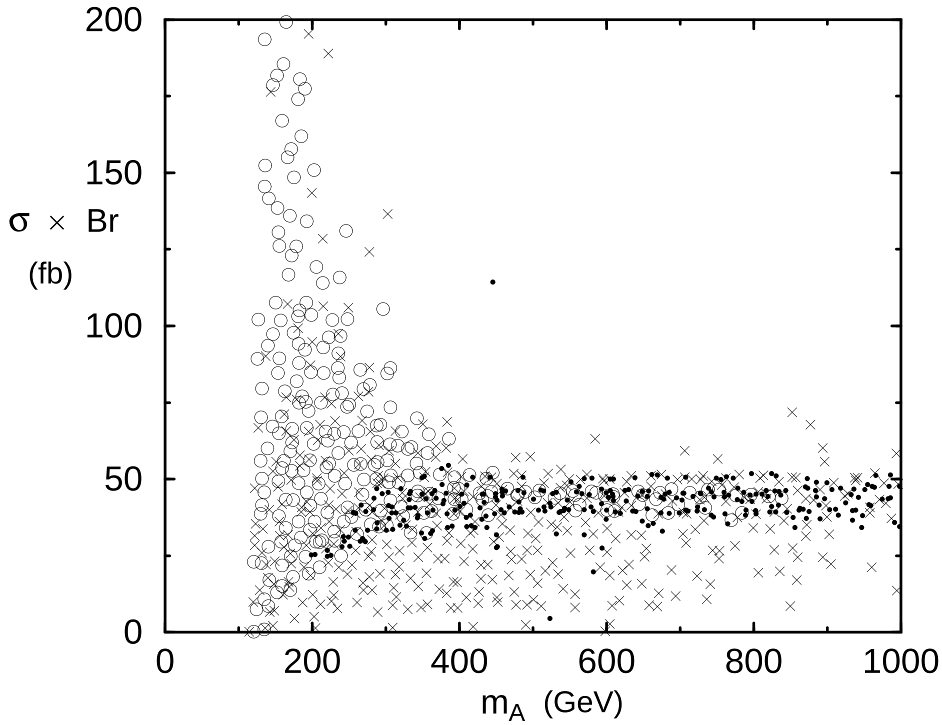

Figure 7: